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An Apparatus for the Evaluation of Web Heating Technologies: Development, Capabilities, Preliminary Results, and Potential Uses

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An Apparatus for the Evaluation of Web Heating Technologies: Development, Capabilities, Preliminary Results, and Potential Uses

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Abstract

It is generally acknowledged that web preheating improves press performance by lowering the viscosity of the water internal to the web. Improvements in web preheating translate into immediate improvements in press efficiency. Steam boxes are the universally accepted devices for preheating the web. However, there is little or no accessible literature on how best to employ steam boxes.

The Institute of Paper Science and Technology, IPST, has designed, built, and tested an apparatus for evaluating web heating technologies. The apparatus consists of a sled, a track for the sled, a steam box, and a vacuum box (if specified). A single instrumented sheet is mounted on the sled, and the sled is propelled, at paper machine speeds, down the track under the steam box. The intent is to expose the instrumented sheet to the same thermodynamic and aerodynamic conditions that a continuous web experiences on a paper machine. Preliminary experiments demonstrated that the apparatus is an effective tool for investigating, under dynamic conditions, most factors affecting steam box performance. The experiments also show that a number of variables affect the ability of the steam box to thoroughly heat the web. One of the most significant variables is vacuum level at the underside of the sheet. The apparatus can be used to investigate both web heating problems on specific paper machines and fundamental processes in web heating.

Introduction

The Institute is currently working to develop an understanding and a database for the commercialization of advanced water removal systems based on impulse drying principles. If successfully implemented, this new technology will reduce capital costs, increase machine productivity, reduce energy consumption, and improve sheet properties.

Sheet preheating is important to conventional pressing, as well as to impulse drying. Increasing the temperature of a moist sheet decreases the viscosity of the water, allowing more water to be transferred at a given press load.

Previous work [1] has shown that impulse drying performs optimally when the sheet is prepressed as much as possible before entering the impulse dryer. An effective way to increase the press dryness entering the impulse dryer is to preheat the sheet as much as possible before each upstream press.

Figure 1, taken from previously published data [2], shows the effect of preheat temperature on press dryness for a simulated single-felted roll press operating at a press impulse of 0.037 MPa·s.

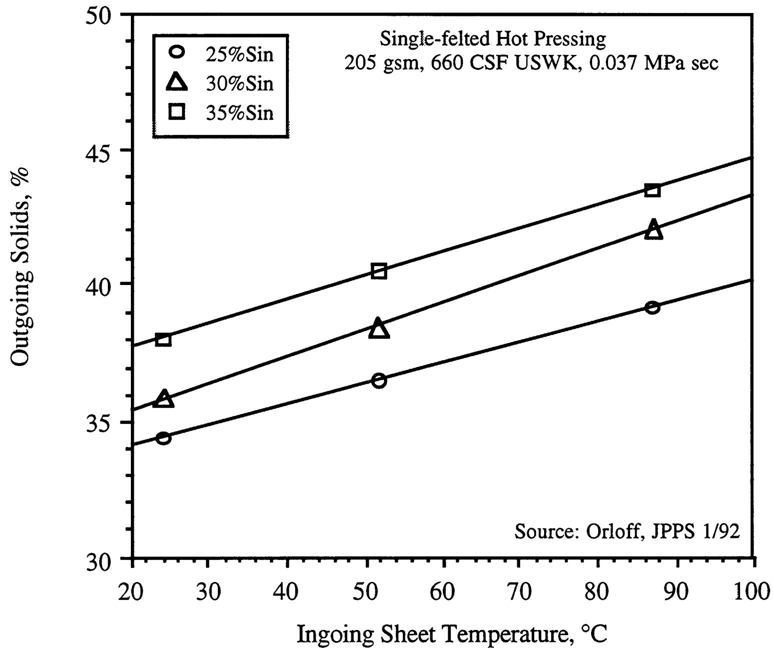

Figure 1. Preheating Improves Single-felted Hot Pressing.

It is observed that outgoing solids increases by about 3 percentage points with an increase of sheet temperature from 50°C to 80°C. A general rule of thumb, for dryer-limited paper machines, is that for every 1% point increase in dryness, at the press section, a 4% increase in machine productivity should be expected. By increasing the sheet temperature from 50°C to 80°C, prior to a single-felted press, a machine productivity increase of about 12% should be realized. Hence, improved design and utilization of preheating devices could have significant bottom-line implications.

Discussions with industry representatives suggest that sheet preheating, usually through the use of steam boxes, is inadequately understood. Some companies report improved pressing efficiency by using steam boxes. Other companies report that they have removed steam boxes because, either they never worked or, through changes in furnish, they no longer work as well as they had previously. Review of the preheating literature suggests that very little engineering heat transfer data exist for steam boxes. Thus, a thorough understanding of the variables affecting the preheating process is needed to optimize both impulse drying and conventional pressing.

Experimental Apparatus

The work presented utilized a new and unique experimental apparatus. The apparatus is officially referred to as the Steam Box Comparator and unofficially referred to as the "Rocket Sled." Although there is no rocket associated with the device, the unofficial name is somewhat more descriptive of the operation of the apparatus. At the time of this work, the apparatus consisted of a sled (Figure 2), a track (Figure 3), a steam box, and a vacuum box. A single-instrumented sheet was mounted on the sled, and the sled was propelled, at typical paper machine speeds, down the track under the steam box. The purpose was to expose the instrumented sheet to the same conditions, both thermodynamic and aerodynamic, that a continuous web experiences on a paper machine.

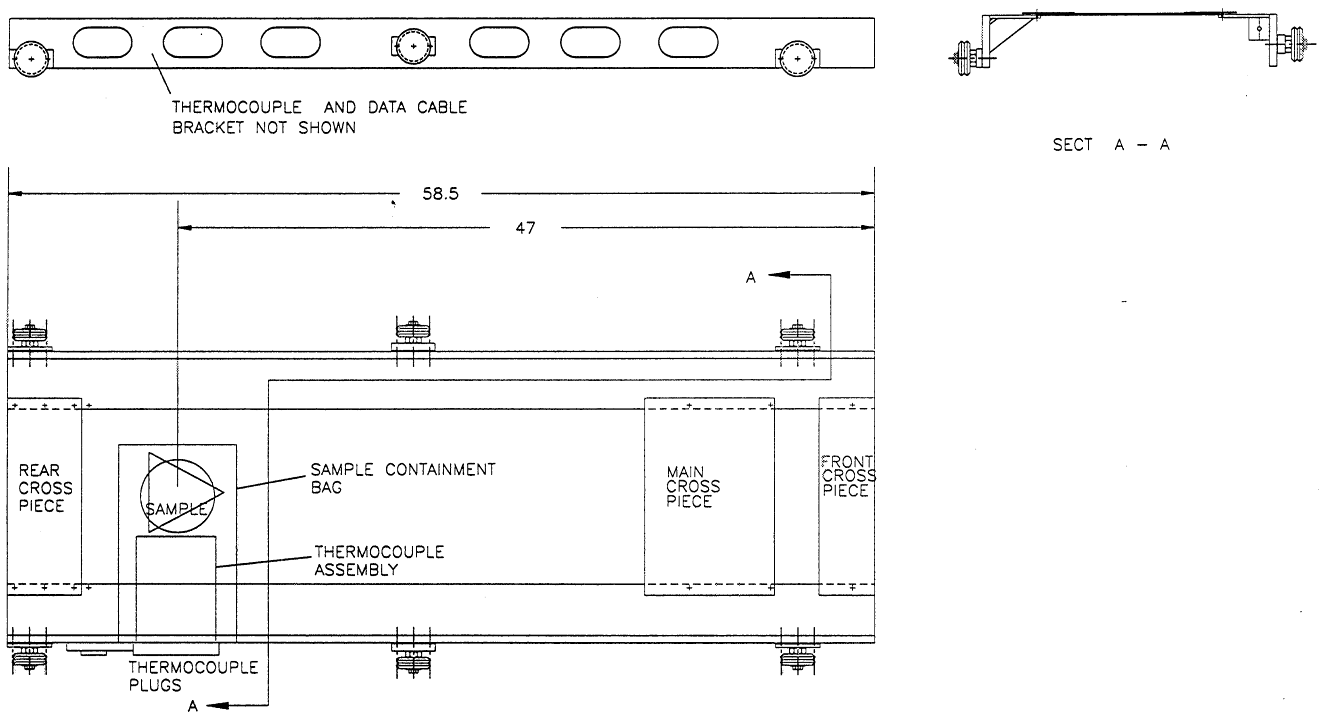

Figure 2. The "Rocket"Sled.

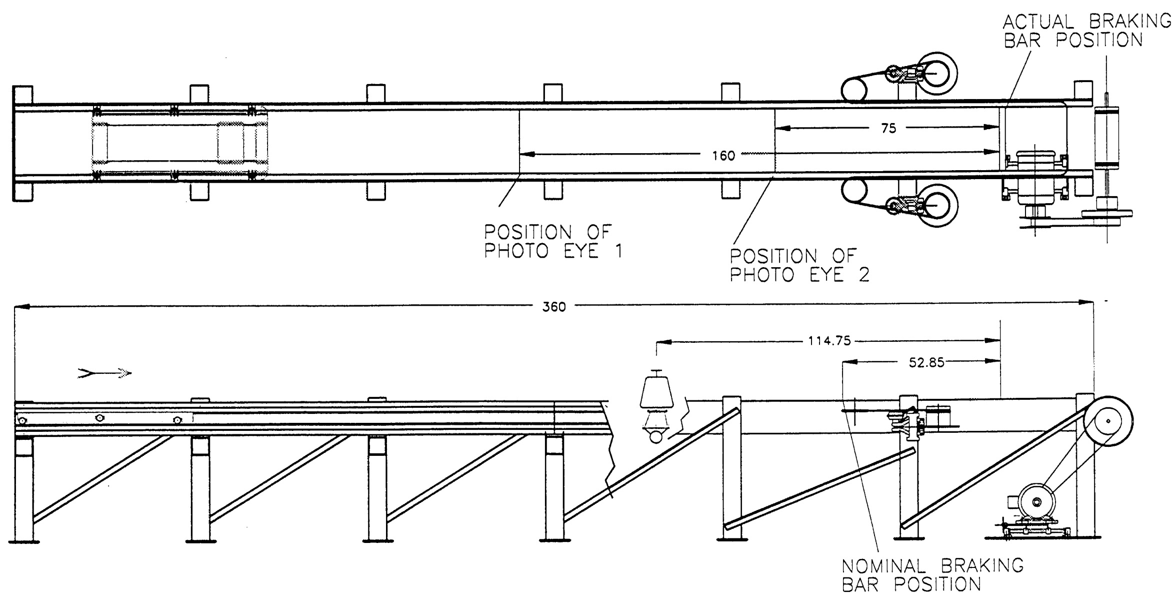

Figure 3. The Track.

The work presented had the objectives of developing the methods needed to make the Steam Box Comparator an effective research tool and of performing preliminary experiments to evaluate the use of a vacuum box in conjunction with a steam box.

Capability of the Apparatus

The Steam Box Comparator is an integrated experimental system that can be used to investigate web heating and drying. It is currently configured for steam and vacuum box investigations; however, with relatively simple modifications, it could be used to study infrared, microwave, hot air drying systems, as well as vacuum systems. The Steam Box Comparator has the ability to:

- Simulate paper machine speeds from 150 m/min to 1050+ m/min.
- Accommodate any sheet-heating apparatus which can be mounted on the track. The apparatus can be wider than 0.64 m wide track; however, the test sample will be exposed to only a 0.64 m wide section of the apparatus.
- Accommodate any grade of paper with sheet sizes up to 0.3 m wide x 0.3 m long. Longer sheets can be used, but the front edge will not experience the same aerodynamic conditions as the trailing edge.
- Accommodate any type of felt or wire.
- Provide steam quality ranging from saturated to superheated (165 °C, 0.3 Mpa).
- Measure steam mass flow rate using a temperature- and pressure- compensated vortex flowmeter.
- Use any combination of 16 analog and 8 digital data acquisition system input signals, sampled at 1000 Hz per channel.

Experimental Methods Development

Use of the Steam Box Comparator for web heat transfer studies required that procedures for forming a multi-ply sheet with embedded thermocouples, pressing such a sample, maintaining the sample moisture content, and sample handling be developed. The procedures addressed the following questions:

- Do the interfaces between plies of a multi-ply sheet cause the sheet to heat differently than a two-ply sheet?
- What is the best method for embedding thermocouples in the sheet?
- How fast does moisture evaporate from a felt under different ambient conditions?
- How fast does moisture evaporate from a sheet under different ambient conditions?

Multi-ply vs. Two-ply Sheets

The effect of ply interfaces on sheet heating was investigated through a series of static steaming experiments. The experiments had two goals: 1.) determine if multi-ply and two-ply sheets produce the same temperature profiles when exposed to a steam jet, and 2.) determine if 17 g/m^2 or 34 g/m^2 plies should be used as the top layers of sheets in future experiments. If multi-ply sheets have the same temperature profile as two-ply sheets, then the method of forming the sheets from plies does not affect the heat transfer process. If 34 g/m^2 top sheets provide adequate data, then fewer thermocouples are required per experiment.

These static steaming experiments employed two types of multi-ply sheets (Types 1 and 2), five types of two-ply sheets (Types 3 through 7), and several single-ply sheets. The basis weight of each complete sheet was 204 g/m^2. Figure 4 shows a matrix of the types of sheets made and the basis weight of each ply used. The individual plies were produced using a British handsheet mold and 450 CSF, virgin unbleached Kraft pulp.

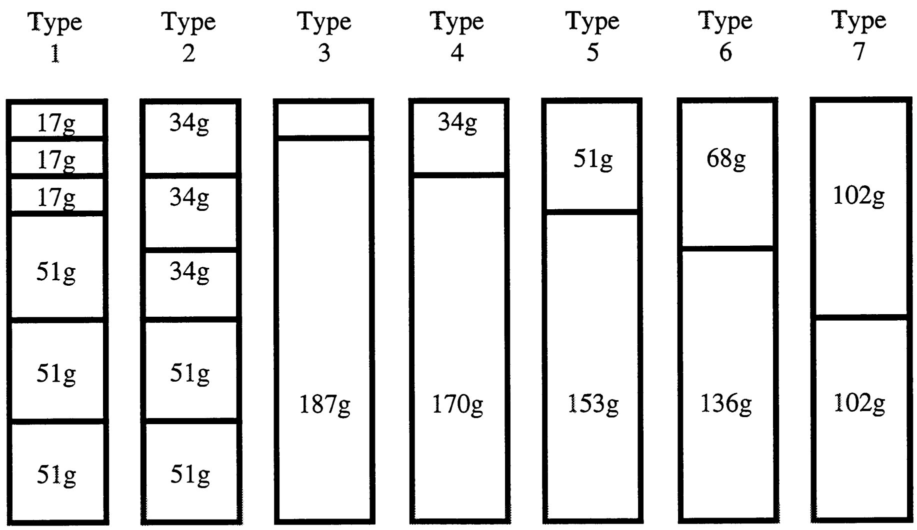

Figure 4. Sheet Construction for Static Steaming Tests.

The composite sheets were formed just prior to the experiment using a hand-operated hydraulic press. This was done to ensure that water contained within the sheets did not migrate. Thermocouples (0.05 mm diameter, type E) were embedded between each ply, with the junctions positioned so as not to be on top of one another. The procedure for forming the composite sheets was to spray each ply with deionized water, lay it on the lower surface of the press, position the corresponding thermocouple on top of the sheet, and then wet and place the next ply on top of the thermocouple. The process was repeated until all plies and thermocouples were in place. Once all layers were in place, the assembly was pressed at 0.7 MPa for 1 minute. This produced sheets that were slightly drier than required (i.e., 30% solids). Prior to the experiment, the sheets were sprayed to increase the moisture content.

The different sheet types were subjected to the same steam flow conditions for identical time periods. The two principal conclusions from this series of experiments were 1.) that it was acceptable to use a multi-ply sheet to collect temperature profile data since the ply boundaries did not appear to affect heat transfer, and 2.) sheets with 17 g/m^2 top plies were required in cases where a complete temperature profile was desired. Figure 5 shows a comparison of the temperature response of Types 1, 2, and 4 at 34 g and Types 1, 2, and 7 at 102 g from the top of the sheets. The response is typical of the other sheet constructions.

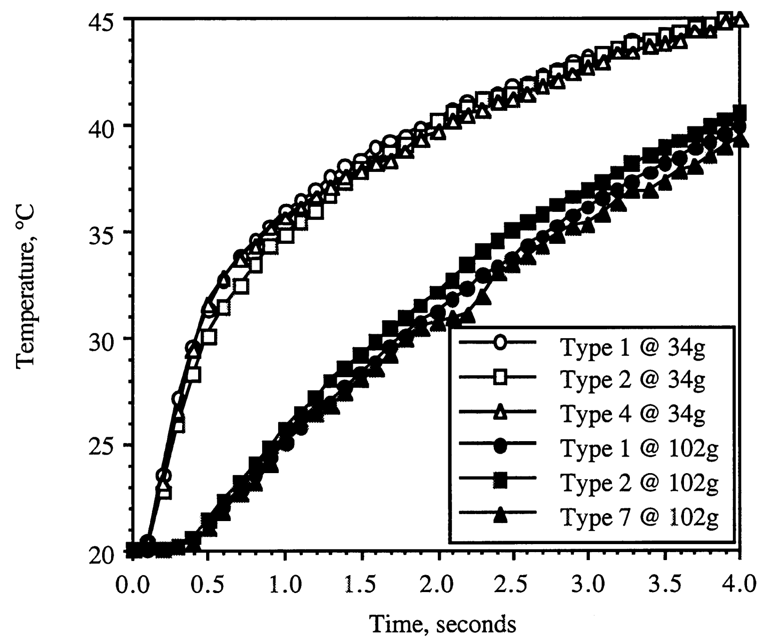

Figure 5. Temperature at the 34 g and 102 g Level from the Top Surface as a Function of Time During Steaming of Multi-ply and Two-ply Sheets.

Sample Construction

The static steaming experiments demonstrated shortcomings in the methods used for forming the sample, embedding thermocouples, and handling the sample. Thermocouple management presented a difficult problem during the fabrication and pressing of the sample. Sample handling also created problems; thermocouples occasionally pulled out of the sample, and the thermocouple wires occasionally crossed resulting in electrical shorts. Efficient testing of numerous samples required development of alternative methods. In addition, there were the problems of pressing the sample, attaining the desired moisture content after pressing, and maintaining the moisture content until the sample was mounted on the Steam Box Comparator.

The first issue considered was sheet construction for a 204 g/m^2 sheet, i.e., the number and basis weight of each layer. The static steaming experiments showed that low basis weight layers (17 g/m^2) were required at the top of the sheet. The samples used in the static experiments had constructions of 34-34-34-51-51 and 17-17-17-51-51-51 g/m^2. While the second of these provided good resolution at the top of the sheet, neither provided for adequate resolution throughout the rest of the sheet. An alternative construction of 17-17-25-25-51-69 g/m^2 was devised. This construction had the advantages of adequate temperature resolution through the entire sheet and relatively easy formation with respect to handsheet forming and individual ply handling. A 17 g/m^2 ply was the lowest basis weight ply that could be consistently formed. The two top plies could be made from top sheet pulp and the remaining plies from base sheet pulp, thus forming a "commercial-like" two-ply sheet.

Felt and Sheet Evaporation

A series of experiments were conducted to ascertain the rates of moisture evaporation, under different ambient conditions, from felts and sheets. Once the evaporation rates were known, it was a simple matter to develop experimental procedures to maintain felt and sheet moisture levels during the experiments.

The felt testing method was as follows. A clean dry (under typical ambient conditions ~27 °C, ~70% RH) felt was cut and weighed. The felt sample was then saturated with water and shaken vigorously to remove excess moisture until a target water content was reached. The felt sample was placed on the scale and its mass measured over time. The ambient conditions were also measured during the experiment. Evaporation experiments were conducted at ambient temperatures between 22°C and 30°C and at ambient relative humidities between 50% RH and 70% RH. The sample size was approximately 305 mm x 305 mm and was of the same material used for the Steam Box Comparator shakedown experiments.

The experiments produced a relatively constant evaporation rate of approximately 0.155 g/min (with a standard deviation 0.018). Since evaporation was slow over the range of ambient conditions, it was concluded that felt moisture content would not change appreciably during the 2 minute time span of an experiment. However, felt moisture can change during the interval between experiments. Attachment of the felt to the sled using zippers made it possible to remove the felt after each experiment, to add water, and weigh the felt sample prior to the next experiment.

A number of sheet samples were formed using the 17-17-25-25-51-69 g/m^2 construction. These samples were pressed at 0.5 MPa for 40 seconds with a target moisture content of 30% solids. The samples did not contain embedded thermocouples. The testing method was the same as used for the felt moisture evaporation experiments.

For the same range of ambient conditions used in the felt evaporation experiments, the results showed that the sheet evaporation rate was relatively constant at 0.027 g/min (with a standard deviation of 0.003). Hence, exposing a sheet sample to ambient conditions for 2 to 3 minutes, while the sheet sample is being mounted on the Steam Box Comparator, should not significantly alter its moisture content.

Thermocouple Assembly

The issue of thermocouple management was addressed by developing a reusable thermocouple assembly. The assembly consisted of five thermocouples, five thermocouple male connectors, and a 152 mm x 203 mm plastic bag used as a backing. One lead of each thermocouple wire was fished through a small diameter plastic tube. The tube was just long enough to allow placement of the thermocouple junction near the center of the sample without the tube interfering with the sample. The plastic bag was cut along the seam opposite the zip seal. The thermocouple lead (Type E, 0.05 mm dia.) without the plastic tube was fed through the bag to the zip seam. The lead with the plastic tube was laid on top of the plastic bag, the free end at the zip seal edge. Both leads were taped in place with masking tape. The free ends of the thermocouples were attached to the thermocouple connector terminals. The thermocouple connectors were spaced on 25 mm centers and clamped to the zip seal edge of the plastic bag. Each connector had a small screwed-on cover used to shield the thermocouple wire terminals; this cover was used to clamp the connector to the plastic bag. The free thermocouple junctions were folded back onto the backing bag and held in place with small pieces of tape. This assembly kept all the thermocouples in place, maintained the orientation of the connectors, and greatly minimized the chance of thermocouple electrical shorts. These assemblies were durable and easily reused. Larger diameter thermocouples would have simplified the process, but their time response was judged to be too slow.

Sample Containment Bag

A second plastic bag was used to contain the sample and thermocouple assembly. A bag measuring 406 mm x 305 mm with the zip seal on one 305 mm edge was cut to 406 mm x 203 mm. This eliminated one of the seams adjacent to the zip seal. The seam opposite the zip seal was cut so the bag could be opened like a book; the one remaining seam acted as the binding. Using a template, and with the bag unopened, an equilateral triangle was cut in both layers of the bag. The triangle was located approximately 76 mm from the zip seal, one side parallel to the remaining bag seam. Each side of the triangle was 127 mm long, see Figure 2. The bag was opened, like a book, and the thermocouple assembly was positioned so that the line of thermocouple connectors was parallel to the zip seal and along the edge opposite the zip seal. The thermocouple assembly was taped in place using masking tape. The bag was closed, and each triangle cutout was covered with a piece of additional plastic which was taped in place. The plastic cover pieces were removed just prior to testing to expose the sample to the steam and vacuum.

Sample Assembly

All of the sheet plies were made prior to assembling the sample, using a standard British handsheet mold. After forming, the sheets were die cut to 127 mm diameter circles. The procedure for fabricating the sample began by weighing and recording the containment bag weight. The bag was opened; the bottom ply of the sample was sprayed with deionized water, and placed on the same side of the opened containment bag as the taped-down thermocouple assembly. The tape holding down the first thermocouple junction was removed and the junction placed approximately at the center of the ply. It was held in that position. The next ply was sprayed and gently placed on top of the thermocouple and the previous ply. This process was repeated until all plies were in place. The embedded thermocouples were numbered from bottom to top as 6, 5, 4, 3, and 2. (Thermocouples 7 and 1 were placed beneath and on top of the sample, at the time of the experimental run). The bag was then folded closed and positioned on a press so that only the sample portion was in the press. The sample was pressed at 0.5 MPa for 40 seconds. This resulted in good adhesion between plies. Afterward the sample was weighed to ensure that it was at the desired moisture content. Deionized water was added or allowed to evaporate as needed. The zip seal of the containment bag was then sealed and the two open edges of the bag sealed with masking tape. The sealed bag was weighed and the weight recorded. The containment bag was small enough so that sample movement was restricted, preventing the thermocouples from pulling out. The thermocouple assembly remained stationary relative to the sample with the connectors all in the proper orientation and order. Corresponding thermocouple plugs were mounted on the sled allowing for quick connections and disconnections. The bag remained sealed until just prior to the experiment, maintaining the moisture content of the sheet. A number of samples were assembled using the above techniques.

Shakedown Experiments

The Shakedown experiments had the following objectives:

- Show that the sheet was exposed to a vacuum.
- Show that the thermocouples and transducers could withstand the loads produced during an experimental run.
- Show that the data acquisition system worked adequately.
- Show that the Steam Box Comparator was a viable experimental tool capable of producing useful data.

Dynamic Vacuum and Pressure Experiments

While it is possible to show, analytically, that a turbulent boundary layer of appropriate thickness will form on the top surface of the sled, it was not so easily shown that a vacuum seal was produced on the underside of the sled.

To verify that the Steam Box Comparator produced a vacuum seal, a dynamic experiment was carried out. Two identical experiments were run, the first with the transducer mounted on the vacuum box manifold, and the second with the transducer mounted, between the sheet and felt, on the sled. The conditions for the experiments were no steam, full vacuum, and sled speed of 790 m/min. Figure 6 combines the results of the two experiments. These experiments show that the average vacuum in the vacuum manifold was approximately 0.084 MPa. Note that the duration of the manifold vacuum pulse corresponded almost exactly to the length of the sled; i.e., the vacuum pressure pulse started almost exactly when the front of the sled reached the vacuum box and ended when the rear of the sled passed the vacuum box. The vacuum pulse recorded between the sheet and felt reached a maximum level of approximately 0.096 MPa. The experiment proved that a vacuum seal was created with a pressure drop of about 0.012 MPa across the felt.

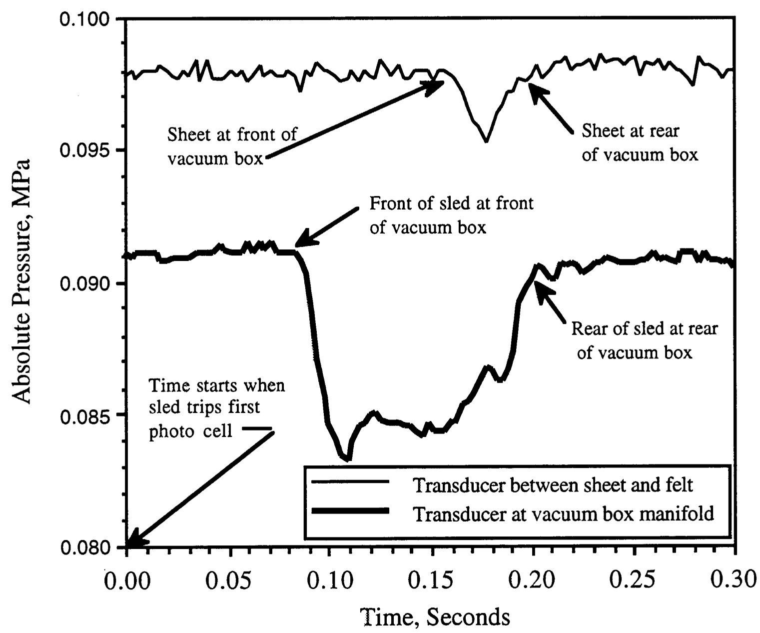

Figure 6. Pressure Measurements Between Sheet and Felt and at Vacuum Box Manifold Versus Time.

Final Shakedown Experiments

Final shakedown experiments were conducted with the intent of collecting data under realistic test conditions. The steam box used was a general purpose Devronizer. The sheet construction for these experiments was:

- 600 CSF, virgin Kraft fiber.
- 204 g/m^2.
- Construction top to bottom: 17, 17, 25, 25, 51, 69 g/m^2.
- Samples pressed at 0.5 MPa for 40 seconds.

The experiments were all run at a sled speed of 610 m/min under the following conditions:

- Constant steam flow, 150 kg/hr, 0.15 MPa, 112 °C.
- Four vacuum levels, 100%, 67%, 33%, 0%.
- Two solids contents, ~30%, ~38%.

The vacuum level was adjusted by opening a vent in the vacuum line. Hence, percent vacuum, in the above, corresponds to the percent area of the vent that was closed. When the vent was fully open (open vent area = 0.01 m^2), the vacuum manifold was at atmospheric pressure (0.101 MPa). When the vent was fully closed (open vent area = 0.00 m^2), the vacuum manifold was at an absolute pressure of 0.084 MPa. As manifold pressure was expected to be linearly proportional to the open vent area, the manifold pressure at the other vacuum box settings could be determined. Figure 7 summarizes the conditions for each of the experiments that was conducted.

Run	Vacuum, %	Manifold Pressure, MPa	% Solids	Comments
1	100	0.084	38	
2	100	0.084	30	
3	100	0.084	38	plastic between sheet and felt
4	67	0.088	30	
5	33	0.094	30	
6	0	0.101	30	

Figure 7. Final Shakedown Experiment Conditions.

At a speed of 610 m/min, the sample reached the steam box at 0.200 seconds, exited the steam box at 0.230 seconds, and hit the brake bar at 0.384 seconds. The braking bar was positioned 1.2 m past the second photo eye. These times are based on the triggering of the first photo eye and may vary slightly from experiment to experiment. The data rate was 125 Hz.

Discussion of Results

Figures 8 and 9 show temperature versus time data plotted as temperature profiles through the sheet at various significant times. The profiles of Figure 8 show the temperatures through the sheet for the case where the vacuum box was running at 0% vacuum, Run #6. The profiles of Figure 9 show the penetration of temperature through the sheet for the case where the vacuum box was running at 100% vacuum, Run #2. It was observed that the use of vacuum significantly improved the penetration of heat into the sheet.

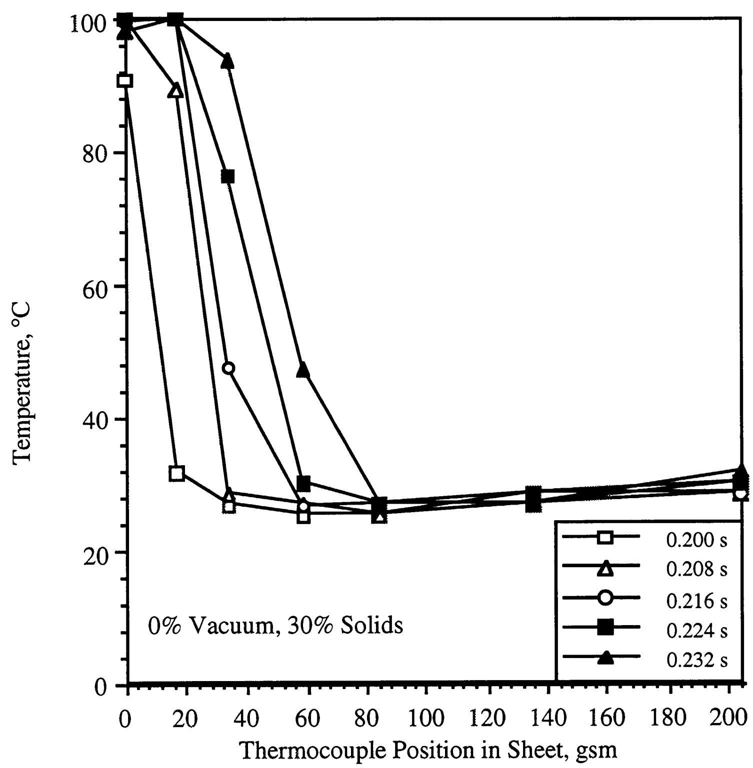

Figure 8. Temperature Profile During Steam Preheating, With No Vacuum.

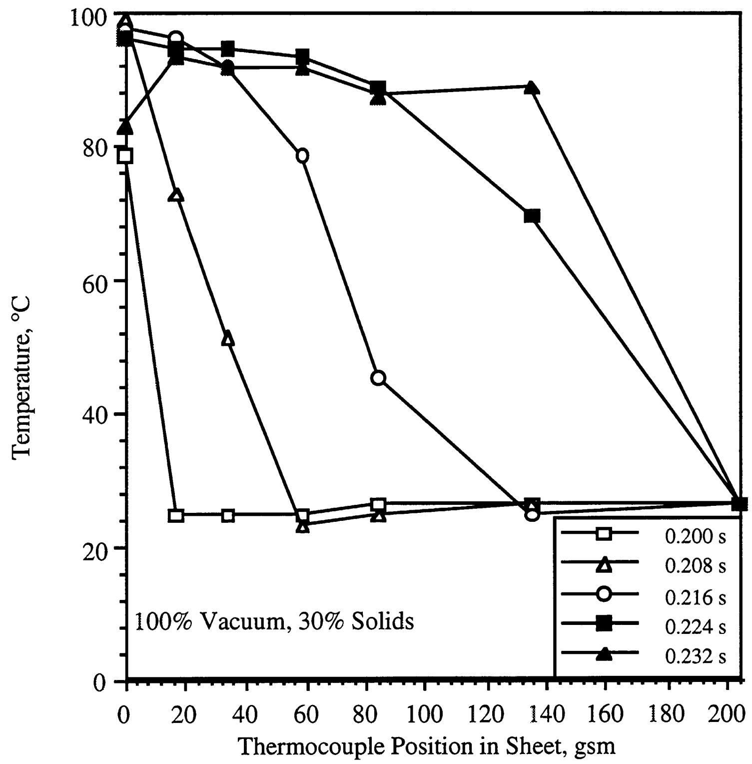

Figure 9. Temperature Profile During Steam Preheating, With Maximum Vacuum.

Figure 10 shows the weighted average temperature, T_{ave}, for all six runs. Where T_{ave} is calculated as

$$T_{ave} = \left[\frac{1}{BWT}\right]\sum_{i=1}^{n}\left[\left(\frac{T_i+T_{i+1}}{2}\right)(BWT_i)\right]$$

Where,

T_i = Temperature on the upper surface of layer i.

T_{i+1} = Temperature on the lower surface of layer i.

BWT = Total basis weight of the sheet.

BWTi = Basis weight of layer i.

n = Total number of layers making up the sheet.

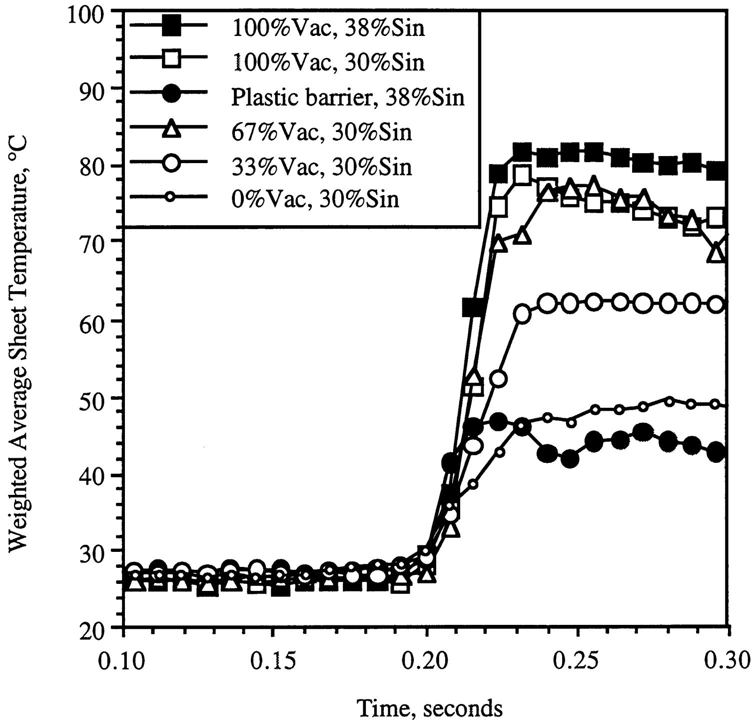

Figure 10. Weighted Average Sheet Temperature Versus Time Through Steam Box.

Figure 10 is useful in obtaining an overall comparison of the runs. A comparison of Runs 2, 4, 5, and 6 shows the effect of vacuum on the average exit temperature of the sheet. In these runs, the vacuum levels were progressively reduced from 100%, to 67%, to 33%, and to 0%. Runs 2 and 4, with 100% and 67% vacuum, show almost identical heating. Despite reaching the same peak temperatures, Run 4 cooled faster. Runs 5 and 6, with vacuum levels of 33% and 0%, respectively, show the effects of further reducing the vacuum. Both the later runs show lower peak temperatures and lower temperatures at braking bar impact.

At 100% vacuum, the pressure in the vacuum box manifold was 0.084 MPa, while the pressure between the sheet and felt was approximately 0.096 MPa. Hence, the pressure drop across the felt was approximately 0.012 MPa, while the pressure drop across the sheet was approximately 0.007 MPa. There are a number of questions with regard to the mechanism by which vacuum produces this effect. Vacuum may cause a downward z-direction displacement of water, thus, providing vacant pore spaces in which steam can condense. Alternately, vacuum may reduce the air in the sheet, thereby increasing the sheet's thermal conductivity.

The primary difference between Runs 1 and 2 is the percent solids of the samples. Temperature profiles showed that the 38% solids sheet reached slightly higher temperatures and that those higher temperatures extended deeper into the sheet than for the 30% solids sheet. The 38% solids sheet also appeared to cool faster than the 30% solids sheet.

Runs 3 and 6 illustrate an interesting and potentially useful effect. In Run 3, the plastic was left on the bottom of the sample, thus isolating it from the vacuum. In Run 6, there was no active vacuum applied. In both cases, the vacuum box remained mounted on the track. The Run 3 sheet had lower peak temperatures. Given the results of Runs 2, 4, 5, and 6, which show that increasing vacuum levels increase the level and depth of sheet heating, it appears that the presence of the vacuum box in Run 6 produced a passive vacuum.

It should be noted that the total energy transferred from the steam box to the sheet, depends on the moisture profile as well as the temperature profile through the sheet. While moisture profiles have not been measured in this work, it is anticipated that increasing the vacuum under the sheet may tend to increase the moisture gradients. Hence, while we know how vacuum affects temperature profiles in the sheet, we do not currently have enough information to construct energy storage profiles through the preheated sheets.

Conclusions

A review of the experimental results leads to several general conclusions:

- The Steam Box Comparator is capable of producing experimental data under conditions similar to those that exist in commercial paper machines.
- Using a vacuum box with the current steam box improves heat penetration into the sheet, although the exact mechanisms causing the improvement require further study.
- It appears that a vacuum box with no active vacuum source can apply a passive vacuum to the sheet.

Current and Future Work

Improvements in web heating directly affect the press performance. Steam boxes and vacuum boxes are relatively low-cost capital equipment compared to the rest of the paper machine. Hence, there is potential for gaining press section performance for a small capital investment. The results of the Shakedown experiments show that vacuum affects steam box performance. We speculate that several other factors affect steam box performance. They are vacuum box location and design, steam box design, steam flow rate, steam superheat, residence time, machine speed, sheet permeability, and felt permeability and construction.

There are a number of specific questions that this investigation suggests. In this study, the vacuum box is 0.23 m long, while the steam box is 0.30 m long. The vacuum box was centered underneath the steam box. The questions arise: Is there an optimum vacuum box length for a given steam box and is there an optimum position for the vacuum box in relation to the steam box? Can a passive device provide a large enough vacuum? Given the limited space available in a paper machine, it would be worthwhile learning if a short length vacuum box or passive device performs as well as a long vacuum box.

The shakedown experiments showed that for a sheet made entirely of 600 CSF furnish that increasing vacuum levels increased steam box performance. Is there a vacuum level where this effect drops off? Does it hold true for all webs, including multi-ply webs?

Is there an advantage to using a different felt? The current instrumentation allows for the measurement of the pressure drop through the felt. Experimental methods exist for measuring felt permeability. Thus, the capability exists to evaluate felts both from the standpoint of water absorption and maximizing the vacuum exerted on the sheet.

If the objective is to improve the performance of a specific paper machine, the question needs to be asked; i.e., Which of these parameters can most easily be changed on the paper machine in question? If the parameters are prioritized as to the paper machine operator's willingness to change them, then the selected parameters can be investigated. An example of this type of work would be the evaluation of the actual preheat capabilities on a specific commercial paper machine. This would involve mounting a representative steam box on the Steam Box Comparator and running a sheet sample made from the pulp used on the commercial machine. Actual temperature profiles of the sample could then be used to evaluate the effectiveness of the preheat system.

Another potential subject for a more general study is design optimization. There is almost no current, publicly accessible, literature on the design of steam and vacuum boxes. Currently, two IPST graduate students are engaged in an investigation of the conduction and convection processes that occur as the sheet passes the steam box. These students have made several improvements to the Steam Box Comparator. The two most significant changes are the replacement of the sled pull cables with a felt and the redesign of the sled. The sled is now pulled down the track by a felt which extends the length of the track. The felt is in two sections: the pull section which extends from the take-up drum to just past the vacuum box and the test section which extends from the end of the pull section to the sled. This change ensures that a dynamic seal is created between the felt and the vacuum box, simplifies the methods required to maintain the upper surface aerodynamic boundary layer, and simplifies the operation of the apparatus. The new sled is 1/3 the length of the original. The new felt pull creates a continuous flat surface from the felt attachment point on the sled to the take-up drum, thus, eliminating the need for the sled structure which produces the same effect. The shorter sled is much lighter, thus, making higher sled speeds possible. At this time, the maximum sled speed tested was 1130 m/min, but more than 1220 m/min is a possibility.

Acknowledgment

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